

Analysis and Modeling of Surfzone Turbulence and Bubbles

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LONG-TERM GOALS

Turbulence in the surfzone mixes momentum vertically, transmits stress to the sea bed, influences the structure of the cross- and alongshore currents, and controls the suspension of sediment from the sea bed. In many coastal and shelf environments, the sea-bed is the primary source of turbulence due to bottom induced shear. In the surfzone, the breaking-wave generated turbulence dominates over bottom generated turbulence. Wave breaking is also the source of bubbles in the surfzone. The dynamics of turbulence under breaking waves in the surfzone is poorly understood. The potentially major impacts of vertical buoyancy fluxes due to air entrainment and bubbles are also unknown and have not been considered. Both the distribution and dynamics of breaking-wave generated bubbles and turbulence, and how they are linked are poorly understood. Bubble injected into the water column dissolve and are a major mechanism for air-sea gas fluxes (*Keeling*, 1993). However, uncertainties in bubble dynamics (generation and evolution) and their interaction with the turbulence generated by breaking waves preclude understanding oxygen or carbon dioxide air-sea fluxes induced during various sea-states. Quantitative estimates of the bubble-induced air-sea gas fluxes are important to constraining the global oxygen and carbon dioxide cycles. Bubbles are also scatterers of light and sound. While the effect of bubbles on the acoustics of the upper ocean has long been of interest, more recently bubble induced optical scattering has been shown to highly variable and often exceeds the scattering due to chlorophyll concentrations (*Terrill et al.*, 2001). An improved understanding of bubble dynamics under breaking waves will result in improved understanding of air-sea gas fluxes, organic carbon budgets, and the acoustics and optics of the upper ocean.

Realistic three-dimensional simulations of surfzone hydrodynamics and sediment transport, which are currently being attempted, for example, in the recent nearshore NOPP project, will not be possible without at least a rudimentary understanding of breaking-induced turbulence and bubble dynamics. Long term goals include addressing some of the unresolved science issues through analysis and modeling of existing field measurements to quantify turbulence and bubble dynamics. This will significantly improve both circulation and sediment transport modeling. In addition, with a tested coupled turbulence and bubble model, air-sea gas transfer under breaking waves can be quantified.

OBJECTIVES

Understanding and accurately modeling the three dimensional nearshore circulation and sediment transport are goals of the ONR Coastal Geosciences Program. The vertical structure of the circulation and sediment suspension are a strong functions of the nearshore turbulence and bubble field. Increased understanding of turbulence and bubble dynamics and the development of coupled turbulence and bubble models for use in circulation and sediment transport models will greatly aid in achieving ONR Coastal Geosciences program goals.

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Unresolved science issues are being addressed by further analysis and modeling of existing surfzone turbulence and bubble observations. Results obtained by the modeling and analysis will be extrapolated to air-sea gas exchange in the open-ocean. The specific objectives include:

- Develop new methodologies for estimating dissipation, Reynolds stresses, and buoyancy fluxes in strongly wave dominated environments such as the surfzone (completed).
- Develop single gas component bubble model and test (completed)
- Test a local balance for the turbulent kinetic energy (ongoing) at multiple vertical locations, and estimate the importance of other terms such as turbulent diffusion. (ongoing)
- Develop surfzone depth-scalings for dissipation, void fraction, and bubble buoyancy flux. (ongoing)
- Perform model-data comparisons using the surfzone turbulence and bubble model developed by the PI. (ongoing)
- Build model component for multiple-gas (nitrogen, oxygen, carbon-dioxide) concentration at each bubble radius component of the bubble size spectrum.
- With a constrained bubble source terms, calculate air-sea gas fluxes under different breaking states. Determine the relative importance of short-lived large bubbles versus long-lived small bubbles. Extrapolate results to global oxygen and carbon cycle.

Attainment of these objectives will contribute significantly to furthering the knowledge of surfzone processes, and will move us toward the long term scientific goal of understanding nearshore circulation and sediment transport processes. These scientific goals are of societal significance because of the economic and recreational importance of the nation's beaches.

APPROACH

The model development (programming) and testing work is being done by the PI (Feddersen), as will the model simulations and model-data comparisons. The ongoing field data analysis is being done by the PI in collaboration with John Trowbridge of the Woods Hole Oceanographic Institution. The field campaign consisted of a main instrumented frame was deployed for 2 weeks at the U.S. Army Corps of Engineers Field Research Facility (FRF) at Duck N.C. in approximately 2.5 m mean water depth with the variable tides and wave heights. The main frame was instrumented with a vertical array spanning most of the water column of 4 ADV (Acoustic Doppler Velocimeter) and 4 conductivity cells to measure velocity and void fraction respectively. These measurements of the vertical structure of turbulence and bubbles in the surfzone are unique and had not before been attempted in the surfzone. A pressure sensor was deployed 15 m seaward of the main frame in order to estimate the wave energy flux, and its gradient due to wave-breaking. Beach bathymetry and offshore wave statistics were provided by the FRF.

Field data analysis includes estimating the dissipation from the ADVs, using the frozen turbulence hypothesis and the inertial-dissipation technique (*Trowbridge and Elgar, 2001*). Conductivity measurements will be converted to void fraction using standard algorithms (*e.g., Vagle and Farmer, 1998*). Buoyancy flux (*i.e.*, $-\frac{g}{\rho}\langle\rho'w'\rangle$) are being estimated by combining ADV vertical velocities with void fraction measurements. The vertically separated ADVs are being used to infer the turbulent momentum fluxes, *i.e.*, $\langle v'w'\rangle$ (*e.g., Shaw and Trowbridge, 2001*) that are part of the shear production term in the TKE dynamics. The pressure sensor pair are used to estimate wave-statistics and the wave energy-flux gradient ($d(Ec_g)/dx$) using linear theory.

The basis of the coupled turbulence-bubble model is a standard k - ϵ model (*Rodi, 1987*) augmented with a wave-breaking turbulence source terms in an approach similar to that used for

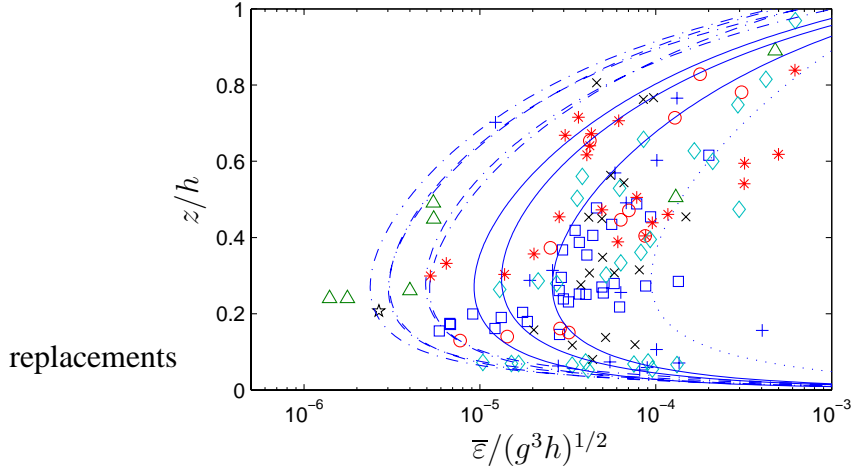


Figure 1: Non-dimensionalized surfzone dissipation $\bar{\epsilon}/(g^3h)^{1/2}$ observations (symbols) and modeled surfzone profiles as a function of normalized height above the bed z/h . The observations come from *Bryan et al.* (2003) (crosses), *Trowbridge and Elgar* (2001) (star), and *George et al.* (1994) (remainder of symbols).

open-ocean wave breaking (*Craig and Banner*, 1994), but with the time-dependence of breaking retained. In addition, the turbulence model is coupled with a bubble model through a buoyancy flux term. The bubble model is based on the bubble transport equation (*Garrettson*, 1973), with a breaking-wave bubble source term, similar to the turbulence source. Both the turbulence and bubble source terms can be constrained by the gradient in wave energy flux. The bubble and turbulence models also are coupled in other ways, for example in the parameterization of bubble breakup due to turbulence (*e.g.*, *Martinez-Bazan et al.*, 1999) As far as I am aware, there has been no prior effort to couple a statistical turbulence model (*i.e.*, k - ϵ or Mellor-Yamada) with a statistical bubble model.

WORK COMPLETED

- Completed testing of single-gas component bubble model
- Test turbulence component of the model with surfzone field observations. Manuscript in revision to *J. Phys. Oceanogr.*
- Developed and tested new methodology for estimation turbulence dissipation in wave dominated environments.
- Developed and tested new methodology for estimating Reynolds stresses in wave dominated environment.

RESULTS

This project is still in the early phases. However, among others, there are two interesting results which will be discussed here. First, the newly developed surfzone turbulence model is able to reproduce the observed non-dimensionalized turbulence dissipation $\bar{\epsilon}/(g^3h)^{1/2}$ from three different data sets (Figure 1). The nondimensionalization of dissipation collapses the three data sets which

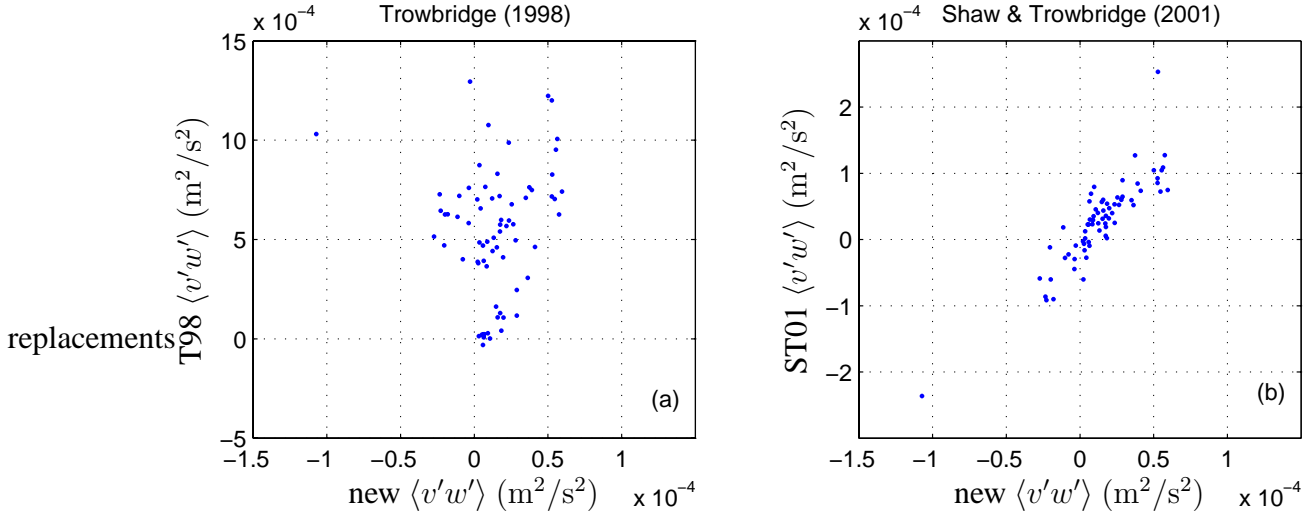


Figure 2: Comparison of Reynold's stress $\langle v'w' \rangle$ estimates. (a) *Trowbridge* (1998) method (T98) derived and (b) *Shaw and Trowbridge* (2001) method (ST01) derived $\langle v'w' \rangle$ versus $\langle v'w' \rangle$ derived with the new method.

come from different beaches and wave conditions. The model curves represent different cross-shore locations in the surfzone. The success of the turbulence component of the model, discussed in much more detail in *Feddersen and Trowbridge* (2004), is extremely encouraging. Field testing of the bubble component of the model is forthcoming.

An important component of testing a turbulence model is developing field estimates of the Reynolds stress component $\langle v'w' \rangle$. As is discussed in *Trowbridge* (1998), estimation of $\langle v'w' \rangle$ in surface gravity wave dominated environments requires special methods. *Trowbridge* (1998) developed a $\langle v'w' \rangle$ estimation method using two current meters and tested it near the bed with two horizontally separated current meters (*Trowbridge*, 1998; *Trowbridge and Elgar*, 2001). *Shaw and Trowbridge* (2001) developed another method for vertically separated sensors with weak wave conditions near the bed off of the continental shelf. For the existing (NSF supported) field observations, a new $\langle v'w' \rangle$ estimation method had to be developed, because the other methods over-estimated $\langle v'w' \rangle$. The *Trowbridge* (1998) method clearly has wave bias problems (only positive $\langle v'w' \rangle$) relative to the new method (Figure 1a). The *Shaw and Trowbridge* (2001) method $\langle v'w' \rangle$ are correlated with but a factor of two larger than the new estimates (Figure 1b). This is related to assumptions regarding turbulence decorrelation length scales made in *Shaw and Trowbridge* (2001).

IMPACT/APPLICATIONS

Potential impacts include vastly improved surfzone circulation and sediment transport modeling through the increased understanding of surfzone turbulence and bubbles created by wave breaking. This is not yet considered in the recently developed (with NOPP support) NearCOM modeling system.

RELATED PROJECTS

The only related project is a NSF award ending December 2004 entitled *Surfzone Turbulence and Bubble Dynamics* in collaboration with John Trowbridge and A. J. Williams of the Woods Hole

Oceanographic Institution. This project provided the field data that continue to be analyzed by this project.

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PUBLICATIONS

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